U.S.G.S. NEHRP Award: 08HQGR0044

Integrated Earthquake Potential Offshore San Diego: A Marine Paleoseismic Investigation

Final Technical Report

Prepared by Jillian Maloney, Daniel Brothers, Jeffrey Babcock

March 31, 2009

Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive
La Jolla, CA, 92093-0225

Program Element III: Research on earthquake occurrence, physics and effects

1. Abstract

To completely understand the seismic hazards in Southern California, it is essential to investigate the behavior and earthquake potential of all fault systems proximal to population centers. During 2008, investigators from Scripps Institution of Oceanography conducted geophysical surveys aboard the R/V Robert Gordon Sproul to study two poorly understood offshore fault zones near San Diego: the San Diego Trough Fault (SDTF) and the Coronado Bank Fault (CBF). Both faults were mapped using a sub-bottom CHIRP profiler, which provided imagery of the recent activity recorded in the upper 30 m of seafloor sediment. Over 500 line-km of high-resolution CHIRP profiles provided constraints on vertical deformation associated with individual paleoearthquakes and, combined with co-located sediment cores, will improve earthquake timing and magnitude estimates. As many as 20 piston cores in the Francis P. Shepard archives at the Scripps Institution of Oceanography were "rediscovered" and will be used to provide chronostratigraphic control on acoustic horizons. Several cores contain organic material that may potentially refine sedimentation history in parts of the San Diego Trough and the Loma Sea Valley. Most faults that were previously mapped were confirmed in the CHIRP imagery. Initial results suggest the most recent rupture on the SDTF occurred during the last 500 years, although further analysis of CHIRP profiles and sediment cores is needed to refine this estimate. The most recent event within the CBF appears to have occurred during the last few hundred years based on the presence of fault propagation folds extending near the seafloor. Some splays show stratigraphic evidence for multiple events. The ~6 m of vertical offset observed along the SDTF is observed along strike for at least 10 km, suggesting the SDTF is capable of producing M>7 events, as well as tsunami run-up along the San Diego coastline. An absence of divergent beds (stratigraphic infill of coseismic deformation) or pelagic drape on the scarp suggests the MRE was recent. The acoustic penetration along the active portions of the La Jolla Fan were limited due to overprint by coarse grained sediment transported from the La Jolla Canyon. Detailed analysis of isopach maps may provide constraints on the long-term horizontal displacement, particularly on the SDTF.

2. Introduction

The recent success of marine paleoseismic methods applied to lacustrine settings (Brothers et al., 2009; Kent et al., 2005) has led to increased motivation to study fault structures in marine environments. High-resolution seismic profiling (CHIRP) provides imagery of the uppermost 30-50 m of sediment, often at the resolution in which discrete depositional events occur. CHIRP imagery, combined with sediment coring and radiocarbon analysis, provide an opportunity to quantify slip rates and estimate timing of paleoearthquakes along faults in submerged settings. Our understanding of the hazards associated with active faults offshore San Diego is limited, especially in comparison with their onshore counterparts. Traditional paleoseismic techniques (excavation, aerial mapping, elevation surveying, etc) have been employed along the onshore reaches of the Rose Canyon Fault and La Nacion Fault Zone in San Diego (Hart, 1974; Lindvall and Rockwell, 1995). Nevertheless, the majority of seismically active faults in the San Diego area are located offshore and are only recently being recognized as potentially hazardous structures (Legg and Goldfinger, 2002). Coastal infrastructure is vulnerable to massive damage and potential loss of life during a large magnitude event on either of these faults; therefore accurate assessment of seismic hazard and the recurrence estimates of large-magnitude events attributed to offshore faults are imperative.

Our surveys were focused on two regions: the San Diego Trough, a deep, narrow, northwest trending submarine basin located about 30 km west of San Diego, and the region between the coastline and Coronado Bank on the south and extending just north of the La Jolla Canyon (Figure 1). During the last 40 years, several studies have resulted in detailed sampling and characterization of Holocene sedimentation along the basin floor, but very little work has focused on the Holocene behavior of the San Diego Trough Fault (SDTF) or the Coronado Bank Fault (CBF), both of which are considered major faults of the CCB.

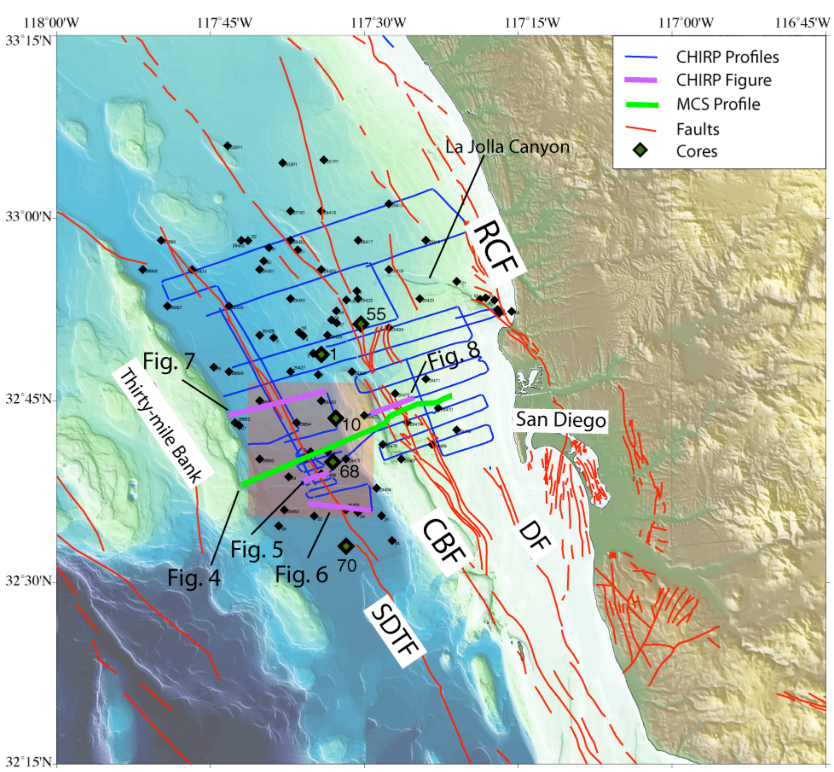

Figure 1. *Shaded relief map of study area. Red lines are active faults in the California Continental Borderland: San Diego Trough Fault, SDTF; Coronado Bank Fault, CBF; Descanso Fault, DF; Rose Canyon Fault, RCF. Blue lines are sub-bottom CHIRP profiles collected in 2007 and 2008. Large diamonds are select cores that have potentially useful constraints on sediment lithology and rates. Shaded region is where nearsurface Isopach maps were generated to investigate lateral heterogeneity in thickness.*

Results of this study are important for updating and improving the seismic hazard models of the metropolitan San Diego region. The primary objectives of this work were to (1) collect and analyze high-resolution seismic CHIRP profiles in an effort to define the regional nature of deformation across the San Diego Trough Fault and Coronado Bank Fault and (2) to establish a chronostratigraphic framework based on radiocarbon samples from existing sediments cores and spatial correlation between CHRIP profiles and co-located cores and (3) constrain the magnitude of vertical components of coseismic slip, a crucial parameter in determining the potential for coseismically generated tsunamis. The results of this study have provided new information on the potential hazards associated with the San Diego Trough- and Coronado Bank faults.

3. Tectonic Setting

The southern California Continental Borderland (CCB) has a rich tectonic history and has been a major player in the evolution of the western margin of the North American plate. As subduction of the Farallon plate beneath western North America waned, the region that is now offshore Southern California was undergoing complex block rotation and transcurrent faulting. During this time (Oligocene to Pliocene), the CCB was experiencing transtensional deformation that formed an extensive system of basins and ridges that are apparent today. During the late Miocene- early Pliocene, plate motion became more northerly (Atwater and Stock, 1998), the San Andreas transform system stepped landward into the Gulf of California-Salton Trough, and the deformation in the CCB decreased dramatically in magnitude and changed in style, becoming dominantly wrench-faulting and less extesional. At present, the active tectonic processes are controlled by a series of wrench fault systems, with the Rose Canyon (RCF), Descanso (DF), Coronado Bank (CBF) and Vallecitos-San Miguel (VSMF) faults (Figure 1) extending nearest to metropolitan San Diego. Based on geodetic models, the San Andreas and San Jacinto Faults accommodate over 80 percent of the dextral plate motion (Becker et al., 2005; Bennett et al., 1996; Meade and Hager, 2005) leaving between 10 and 20 percent (5-10 mm/yr) of the remaining slip budget to be distributed across active structures to the west and offshore (Figure 2). For comparison, this rate is approximately equivalent to that of the Eastern California Shear Zone and the Walker Lane, two heavily studied tectonic provinces.

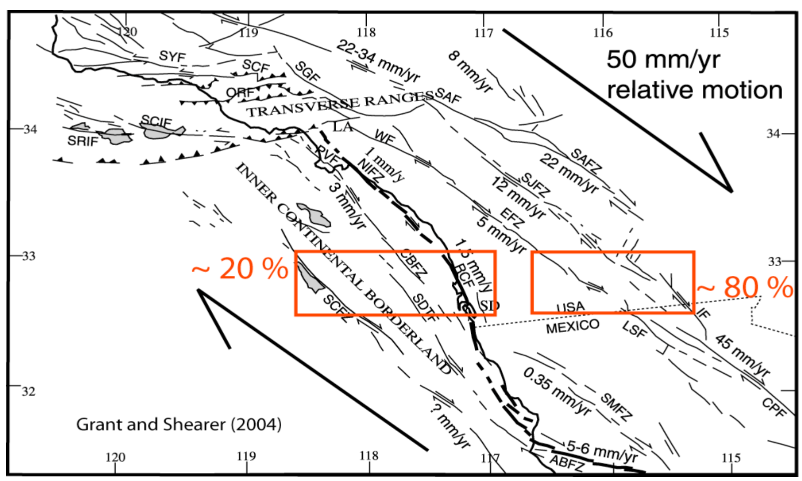

Figure 2. *Fault map modified from Grant and Shearer (2004) highlighting distribution of slip in Southern California. As much as 20% (~10 mm/yr) of North America-Pacific plate boundary deformation is distributed along faults west of the Salton Trough in the Continental Borderland. Nevertheless, deformation rates and earthquake history along offshore fault systems remain poorly understood due to an absence of high-resolution geophysical data.*

Several geophysical and geological studies have delineated fault zones in the eastern CCB near San Diego and have shown evidence for Holocene displacement (Grant and Shearer, 2004; Kennedy and Clarke, 1999; Legg, 1985; Moore, 1969). Both the SDTF and the CBF are considered segments splaying off the Bank-Agua Blanca fault system of northern Baja California (Allen et al., 1960; Dixon et al., 2002). Offshore seismic surveys have delineated fault geometry, but the slip-rates have not been constrained. Astiz and Shearer (2000) relocated earthquakes that occurred from 1981 to 1997 between the Coronado Bank and Point Loma, many of which could be attributed to motion along either the CBF or the Descanso Fault (Figure 2). Additional seismicity includes a spattering of M3 - M4 earthquakes just offshore Point Loma and Mission Bay, a M5.3 earthquake (and aftershocks) along the Coronado Bank Fault in 1984 and reports of a large ~M6.0 earthquake offshore in 1862. Overall, very little is known about the slip rates, earthquake recurrence intervals, and kinematic relationships between various fault systems in the CCB, and consequently, seismic hazard estimates are poorly constrained.

4. Results

Sediment Cores

Several studies during the last 50 years have described the sedimentary processes occurring within the La Jolla Canyon-Fan system and the San Diego Trough (Covault et al., 2007; Emery and Bray, 1962; Legg, 1985; Moore, 1969; Piper, 1970; Shepard and Einsele, 1962). Hundreds of shallow sediment cores (box, gravity and piston) have been collected along the La Jolla Submarine Fan providing information on sedimentary character and rates of deposition. One of our primary objectives was to perform a comprehensive search for existing core data from repositories at the Scripps Institution of Oceanography and the University of Southern California. We were able to locate several cores collected in the 1950's and '60's, which comprise the Francis P. Shepard archives (Table 1). Although completely desiccated, the cores are intact and contain abundant foraminifera for radiocarbon dating (Figure 3). The location of these cores during collection was determined using the LORAN (Long Range Aid to Navigation) method, and, as such, contain uncertainty that is difficult to quantify. Paper records from several cruises indicate that detailed bearings and ranges, as well as water depth were recorded at the time of core collection. For our purposes, the exact core locations are not necessary, as sediment thickness within the SDT is observed to be relatively uniform.

Figure 3. *Select cores from the Francis P. Shepard archives, located at the Scripps Institution of Oceanography. Locations of these piston cores (LC 55 and LC 68) are given on Figure 1. The total length of each is over 3 m. Organic material, mostly a combination of benthic and pelagic foraminifera, is abundant in these samples.*

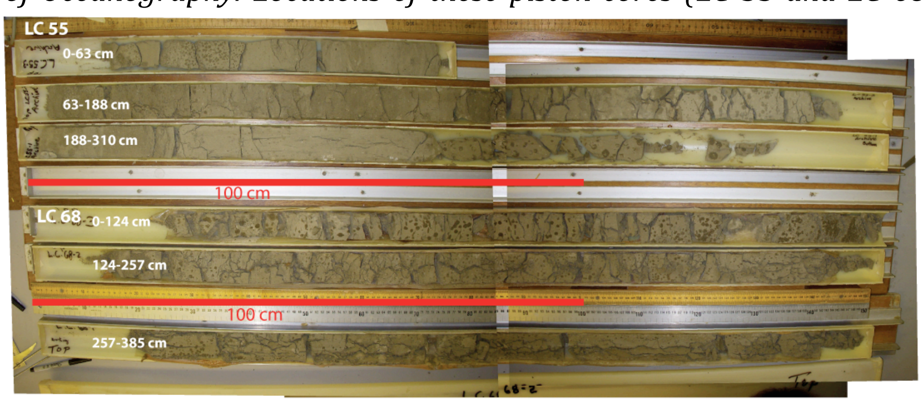

Table 1 : Sediment Cores in and around the San Diego Trough. Bolded cores are highlighted on Figure 1 as being potentially useful for dating.

Core ID	Depth (m)	Length (cm)	Type	Location
1	**899**	**410**	**Piston**	**SIO**
2	973	380	Piston	SIO
7	980	131	Piston	SIO
10	**1025**	**209**	**Piston**	**SIO**
14	1080	109	Gravity	SIO
18	1095	83	Gravity	SIO
19	1128	80	Gravity	SIO
22	1190	80	Gravity	SIO
24	1195	83	Gravity	SIO
31	895	111	Gravity	SIO
46	300	88	Gravity	SIO
54	815	60	Gravity	SIO
55	**780**	**310**	**Piston**	**SIO**
56	920	100	Gravity	SIO
60	496	67	Gravity	SIO
61	922	91	Gravity	SIO
62	895	53	Gravity	SIO
63	1210	805	Piston	SIO
64	1170	368	Piston	SIO
66	1078	265	Piston	SIO
67	1120	60	Piston	SIO
68	**1120**	**385**	**Piston**	**SIO**
69	1200	364	Piston	SIO
70	**1220**	**360**	**Piston**	**SIO**
28892	909	unknown	unknown	USC
28893	1098	unknown	unknown	USC
28894	1170	unknown	unknown	USC
28895	1026	unknown	unknown	USC
29423	549	unknown	unknown	USC
29424	640	unknown	unknown	USC
29425	914	unknown	unknown	USC
29426	1024	unknown	unknown	USC
29462	1189	unknown	unknown	USC
29463	1189	unknown	unknown	USC
29464	1097	unknown	unknown	USC
29467	183	unknown	unknown	USC
29468	238	unknown	unknown	USC
29469	186	unknown	unknown	USC
29470	320	unknown	unknown	USC
29471	317	unknown	unknown	USC
29472	549	unknown	unknown	USC
29473	549	unknown	unknown	USC
29474	494	unknown	unknown	USC

29478	283	unknown	unknown	USC
29479	1125	unknown	unknown	USC
29480	1134	unknown	unknown	USC

Constraints on sedimentation rates in the San Diego Trough (SDT) have been published based on analysis of the cores stored at SIO as well as several cores we could not locate. Piper (1970) calculated that the average thickness of Holocene sediment in the La Jolla Fan is ~2 m based on foraminifera dating. Shepard et al. (1968) calculated a sedimentation rate of 12.6 cm/1,000 yrs on the outer La Jolla Fan based on radiocarbon dates of kelp, while Emery and Bray (1962) calculated a rate for the SDT of 18 cm/1,000 yrs based on radiocarbon dates from a core located in the center of the trough. These rates indicate a depth of Holocene sediment in the SDT of between ~1.3 and 2 m. Covault et al. (2007) have suggested that sediment transport in the CCB offshore San Diego has alternated between the La Jolla fan system and the more northern Oceanside and Carlsbad fan systems with changes in sea level. The La Jolla fan has been the active system during sea-level highstands and was most recently activated at ~13 ka. The activation of the La Jolla Fan may correspond to the prominent reflector observed at ~2 m below the seafloor in several CHIRP sections within the SDT (Figures 4, 5 & 6). Based on the sedimentation rates above, the age of this reflector is between ~11,000 ka and ~15,000 ka. A change in sediment character was not apparent at this depth in the cores we examined from the Shepard archives.

Based on review of published sedimentation rates, examination of cores collected from the SDT, and our geophysical data, we estimate that the base of Holocene deposition is constrained to within approximately 2m below the seafloor, and is likely limited to the pelagic deposition above the prominent reflector observed in the CHIRP data. The low rates of sedimentation may indicate that the SDT is completely filled with sediments such that new sediment bypasses the SDT and is deposited in the San Clemente Basin (Emery and Bray, 1962; Piper, 1970). Additional analysis, including radiocarbon dating, of cores at SIO and USC will help further our understanding of sedimentation in the SDT and better constrain seismic activity on the SDTF.

In addition to the Shepard archives, we were able to locate several cores collected near the CBF, which are currently stored at USC (Figure 1). We could not find any records of radiocarbon dates from these cores and their total lengths are currently unknown. X-radiographs of several cores were recorded at USC and we plan to review digitized copies of those records, which may assist in determining sediment characteristics in the area and interpreting geophysical data. USC also has archived samples of the cores available for future analysis.

Geophysical Data

Over 500 line-km of sub-bottom CHIRP profiles were collected offshore San Diego in 2008 (Figure 1) aboard the R/V Sproul using funds from a student ship-time award. Surveys alternated between 0.7 – 3.0 kHz (50 ms) and 1.0 – 6.0 (50 ms) CHIRP sources depending on the sediment character and water depth. All shots were time-stamped with real-time GPS navigation. Profiles were loaded into Kingdom Suite and IVS Fledermause software suites for interpretation and 3-D visualization. Acoustic horizons were correlated spatially between profiles and used to construct Isopach maps of marker beds that can be correlated with core samples. The following sections highlight significant observations in the CHIRP data.

San Diego Trough Fault

The SDTF is a highly linear dextral strike-slip fault and, with the exception of a couple minor restraining bends (Legg et al., 2007), it shows little stratigraphic or structural evidence for long-term vertical deformation within our focus area of the San Diego Trough (e.g., Figure 4). Distinctive seafloor scarps are observed along the Coronado Fan, south of the international border, but these may be due to horizontally translated fan topography (Legg et al., 2007). Although the central SDTF appears nearly vertical in deep penetration seismic reflection imagery and shows little evidence for divergence at depth, we observe consistent ~6 m high, down-to-the-west seafloor scarps for more than 10 km along-strike.

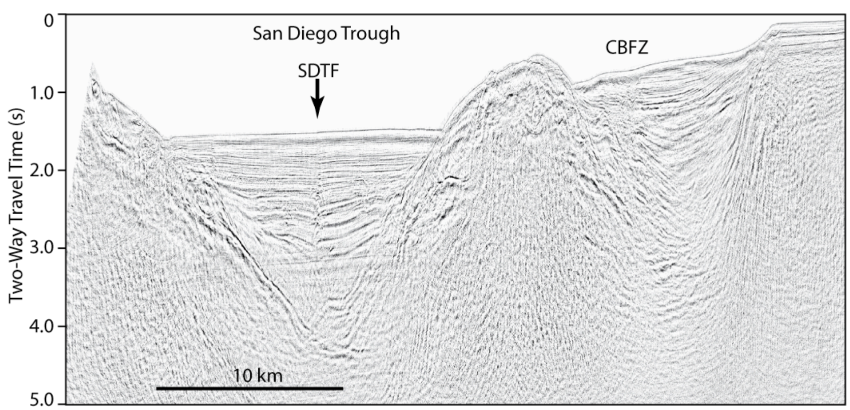

Figure 4. *USGS-Western Geco multichannel seismic reflection profile across the San Diego Trough and San Diego Shelf (see Figure 2 for location). Note the vertical nature of the SDTF and absence of divergent reflectors. See Figure 1 for location. Left=west, right=east*

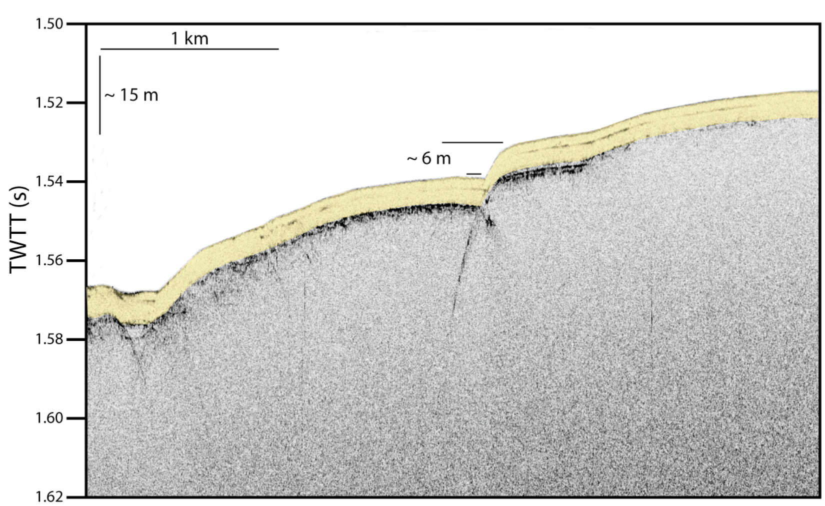

Figure 5. *Example CHIRP section over the SDTF highlighting the 6 m seafloor scarp. The yellow layer is interpreted to be pelagic fine grained deposition since ~ 40 ka. The basal reflector is interpreted to be coarse grained deposits from an earlier active progradation of the La Jolla Fan. See Figure 1 for location. Left=west, right=east*

By correlating the seismic stratigraphy throughout the San Diego Trough and La Jolla Fan we can constrain the spatial heterogeneity of sediment horizons. The isopach map in Figure 7 shows little lateral heterogeneity, suggesting the LORAN-based errors in core locations may not be a problem as long as correlations between key marker beds in cores and seismic stratigraphy can be made.

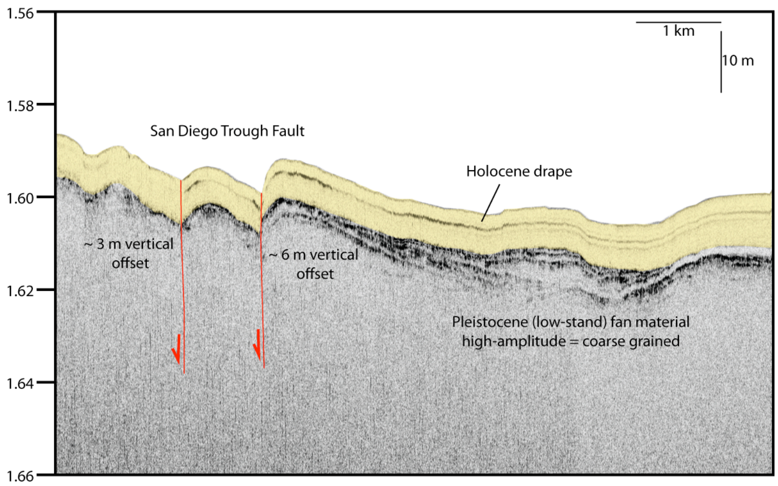

Figure 6 (left). *Southerly CHIRP section where the SDTF slits into two segments. The eastern segment, again, appears to have an ~ 6 m high seafloor scarp. See Figure 1 for location. Left=west, right=east*

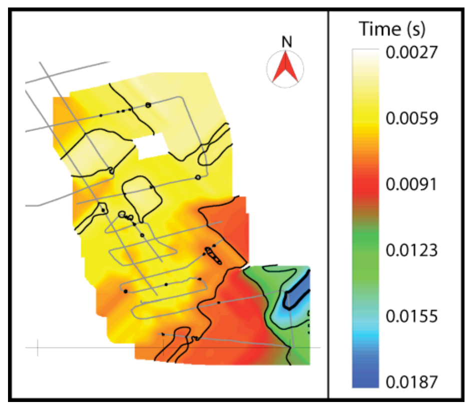

Figure 7 (right). *Isopach map of the pelagic layer (colored yellow in Figures 5 and 6) surrounding the STDF. The spatial extent is shown as a shaded box in Figure 1. The color bar represents thickness as two-way travel time. The greatest sediment thickness on the southeast edge of the map is likely an artifact of CHIRP data collection. Discounting the artifact and assuming a sediment velocity of 1500 m/s means the pelagic layer varies between ~4 – 10 m. Nevertheless, throughout most of the region the thickness of the pelagic sediment varies less than 1 m.*

One limitation we encountered in the northern SDT involved the coarse grained nature of seafloor sediments in the vicinity of the La Jolla Fan channel. Despite sea level high-stand, La Jolla Canyon is actively transporting turbidity flows of sand/silt to the La Jolla Fan (Covault et al., 2007; Piper, 1970). The CHIRP source was limited due to a combination of water depth and high-impedance at the seafloor. Although identification of the SDTF in this part of the trough is difficult, the data gives a constraint on the extent of active coarse grained deposition as the La Jolla Fan spills into the San Diego Trough (Figure 8).

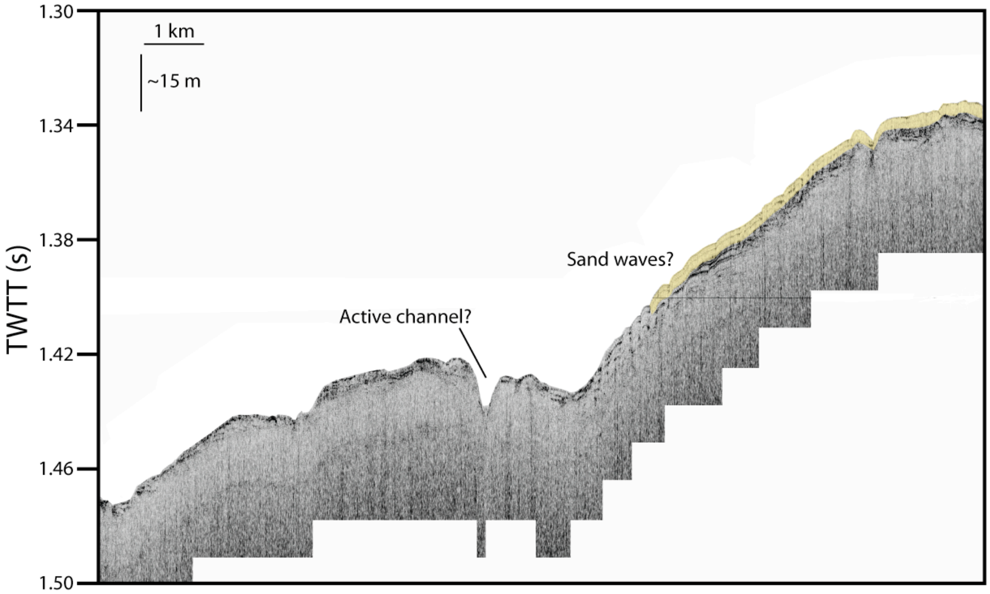

Figure 8. *CHIRP profile off the slope and into the San Diego Trough. Yellow layer is Holocene pelagic drape in areas that are not experiencing coarse grained deposition (Piper, 1970). See Figure 1 for location. Left=west, right=east*

Coronado Bank Fault

The CBF is characterized by several complex strands of left- and right- stepping strike-slip faults. Our goal was to find stratigraphic evidence for paleoearthquakes along the CBF and use chronostratigraphic constraints to estimate the timing and recurrence interval on this fault system. The fault shown in inset A on Figure 9 extends very near to the seafloor. Deformation in the unconsolidated, near-surface sediment is characterized by folding rather than distinctive offset. Stratal patterns in inset B (Figure 9) may be either tectonic or depositional, where coarse grained layers beneath the pelagic drape have infilled topography, that may or may not be tectonically controlled.

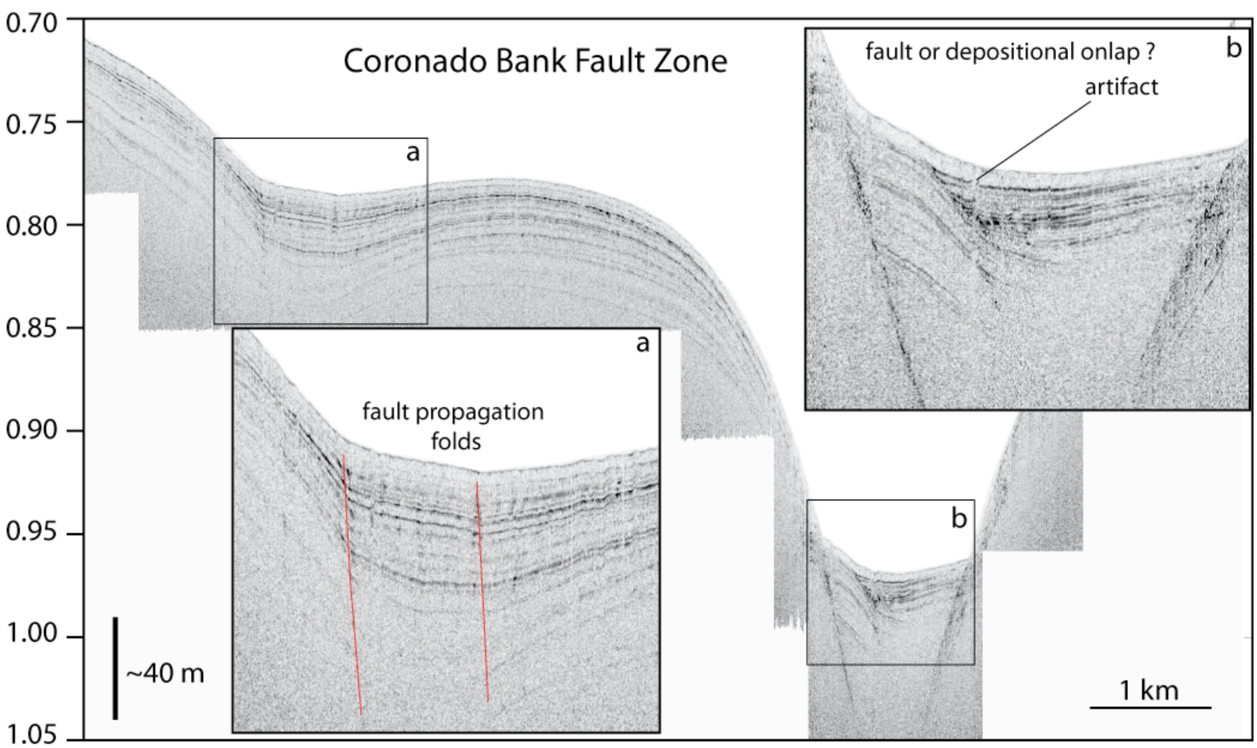

Figure 9. *CHIRP profile over the Coronado Bank Fault Zone. Here we observe 2 fault segments, one of which appears to have two splays. See Figure 1 for location. Left = east, right = west.*

5. <u>Conclusions</u>

The 6 m high seafloor scarps that seem to increase in height to the north are intriguing. We do not observe stratigraphic evidence for multiple events in the CHIRP imagery and the offset appears very recent. This raises several questions regarding the kinematics of the SDTF. Should a single 6 m vertical displacement event occur along the SDTF this may produce an M>7 event (Wells and Coppersmith, 1994), and also the possibility of a tsunami wave. Published sedimentation rates in the San Diego Trough are ~ 16 mm/yr. The fresh character of the scarp and absence of pelagic drape over the scarp face suggests the most recent event occurred sometime during the last 500 years. All layers within the upper 5 m of sediment are displaced the same amount and we estimate the basal, high-amplitude reflector is approximately 40 ka, making the average vertical slip rate ~ .1 mm/yr. Although it is possible that the SDTF has experience only a single large event in the last 40 ka, the sense of slip is not necessarily the same each cycle and older events may have been purely strike slip in nature and would be difficult to detect using standard two-dimensional imaging techniques. We believe this fault has a relatively high slip-rate (~ 2 mm/yr) based on offset geomorphic markers discussed by Legg et al. (2007) and is capable of producing large magnitude earthquakes. Further analysis of CHIRP profiles and detailed calculations of isopach contours may provide a means to estimate horizontal offset across the ~40 ka basal reflector.

The Coronado Bank Fault Zone shows promising results. Several CHIRP profiles show evidence for at least two paleoearthquakes, the most recent of which may have occurred during the last few hundred years. Further analysis of sediment cores east of the Coronado Bank will help constrain sedimentation and fault slip rates. More detailed analysis of geophysical data will also elucidate variations in fault geometry along strike and may clarify the controls on stratal patterns observed in the western canyon of the fault zone.

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